



# Dual-Band Polyester-Based Wearable Bandpass Microstrip Filter Using Stepped Impedance Resonator

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**Abstract-** This research paper presents a compact dual-band polyester-based wearable bandpass microstrip filter using stepped impedance resonator. In the proposed wearable filter, pass band of 1.85 GHz to 2.66 GHz is useful for ISM band and 3.74 GHz to 7.42 GHz is appropriate to Wi-Fi, WLAN and Wi-Max frequency band applications respectively. In this filter, insertion loss of 0.147 dB and return loss of 32.6 dB at 2.38 GHz insertion loss of 0.469 dB and return loss of 32.3 dB at 4.54 GHz with fractional bandwidth of 34% and 81% is respectively achieved. The proposed wearable filter is fabricated using polyester cloth substrate and self-adhesive copper tape. The Agilent vector network analyzer is used to test the fabricated polyester filter. Good agreement is obtained between the simulated as well as measured insertion loss and return loss of the proposed wearable filter. Equivalent circuit and SAR analysis of this filter is also presented in this paper. Novelty of this research paper is fabrication of high bandwidth dual band wearable filter that can be integrated with wearable antenna to be a wearable Filtenna. Modified equivalent circuit of SIR is prepared and validated. Simulated and measured results are found to be in good agreement.

**Index Terms-** polyester, wearable microstrip filter, stepped impedance resonator (SIR), specific absorption rate (SAR), equivalent circuit, transmission line theory (TLT)

## I. INTRODUCTION

Nowadays, wearable flexible microstrip antennas are extensively used in microwave body-centric RF and wireless personal handheld communication devices and found to be useful under 4G, 5G, and 6G technologies [1-4].

These kinds of antennas need flexible wearable filter circuits to effectively select desired frequency bands and to remove unwanted frequency bands. Therefore, it is conveniently needed to make these filters out of cloth or textile material and fit into wearer clothing to wirelessly transmit on-body and off-body data, video, and related information. Cloth-based substrate materials such as polypropylene, cotton, nylon, polyester, foam, nomex, and liquid crystal polymer (LCP) are used to fabricate these devices[1-7].

Most commonly assigned frequency bands for such applications are- body area networks (BAN), industrial, scientific, and medical (ISM), WLAN, Wi-Fi, Wi-max, Bluetooth, HYPER LAN, public safety, etc.

There is a potential need of planar, conformal, compact-size, and multiband microstrip wearable filters for body-worn RF wireless communication devices and systems with broad stop bands to suppress harmonics as well as interference frequency signals and pass desirable frequency bands [5-7]. Moreover, these filters must be lightweight, flexible, and conformal in order to be conveniently encompassed into the wearer's clothing or wearable technology.

Conventionally, rigid and non-conformal microstrip filters using RT Duriod and FR4 substrates have been proposed in the literature [8-17]. Limitations of these filters are- not flexible, cannot bend with respect to wearer positions and difficult to integrate in the clothings. Hence, in this research work a flexible polyester based wearable filter is proposed.





(a)



(b)

Fig. 2. Photographs of fabricated dual-band polyester-based wearable bandpass filter using SIR (a) Filter side (b) Ground plane side.

Fig.2(a) and (b) respectively shows photographs of fabricated dual-band polyester-based wearable SIR filter and its ground plane side. It consists of total thirteen low impedance lines ( $l_{1L}, l_{3L}, l_{5L}, l_{7L}, l_{9L}, l_{11L}, l_{13L}$ ) and high impedance lines ( $l_{2H}, l_{4H}, l_{6H}, l_{8H}, l_{10H}, l_{12H}$ ) in the middle which are connected to each to form a SIR. It has two 50  $\Omega$  impedance lines at the two ends. The SIR structure is end-to-end symmetrical along the dotted line as shown in Fig. 1. It is maximally flat Butterworth filter of 13<sup>th</sup> order that is  $N=13$ . The filter structure consists of a SIR of seven vertical stubs that is low impedance lines, each stub has dimensions; length  $L_2 = 14$  mm and width  $W_2 = 1.5$  mm. Length of vertical stub is  $\lambda_g/4$  that is 14mm. These vertical stubs are connected by a common horizontal stub at the center having six high impedance line sections of length  $S_1 = 4$  mm, width of horizontal stub is  $W_1 = 2$  mm. The microstrip line of width 2 mm and length 4 mm is chosen to have characteristic impedance that matches to a terminating impedance  $Z_0 = 50 \Omega$ . At both ends of proposed filter feed points port 1 and port 2 are respectively connected using SMA connectors as shown in Fig.2. Size of the proposed SIR filter is  $0.46\lambda \times 0.261\lambda$ .

SIR structure generates infinite number of resonant frequencies which may be of odd-mode or even mode. Therefore, for obtaining the significant resonant frequencies the conditions used are expressed by equations (1) and (2).

$$\tan\theta_1 = R \cot\theta_2 \quad (1)$$

$$\cot\theta_1 = -R \cot\theta_2 \quad (2)$$

where; R is the impedance ratio  $R = \left(\frac{Z_2}{Z_1}\right)$ ,  $Z_1$  and  $Z_2$  are characteristics impedances of SIR stubs,  $\theta_1$  and  $\theta_2$  are electrical lengths of the stubs of SIR filter. The proposed SIR filter consists of two lines of different characteristic impedances  $Z_1$  and  $Z_2$  with electrical lengths  $\theta_1$  and  $\theta_2$  respectively as shown in Fig.1. At  $\theta_1$ , the physical length  $S_1$  is 4 mm and at  $\theta_2$ , length  $W_2$  is 1.5 mm. These dimensions determine the resonant frequencies of filter as follows.

The resonant frequencies of SIR filter can be determined and tuned by changing- (a) value of impedance ratio 'R' (b) physical lengths of vertical stubs which is low impedance lines and horizontal stubs that is high impedance lines of proposed filter [9-11], [14]. Impedance ratio (R) of the proposed SIR filter is calculated to  $R = 0.4$  [11]. The conditions used for obtaining resonant frequencies are;  $\theta_2 = 86^\circ$ ,  $\theta_1 = 1.31^\circ$  and  $u = \frac{\theta_2}{(\theta_1 + \theta_2)}$  therefore  $u = 0.984$  [9-11]. A polyester cloth substrate with a thickness of  $h = 3.14$  mm and a dielectric constant  $\epsilon_r$  of 1.39 is used in the design and construction of the suggested wearable filter. The fabricated SIR and ground plane, are cut from 0.1 mm thick self-adhesive copper tape and firmly adhered to the prepared polyester substrate in accordance with the designed dimensions and forms. The method-of-moment based CAD Feko electromagnetic simulator was used to simulate this filter structure.

### III. INVESTIGATION OF GEOMETRICAL PARAMETER VARIATIONS

The design parameters of proposed SIR filter affects its performance parameters such as; FBW, insertion loss, and return loss. Hence, the essential geometrical parameters of the proposed SIR filter have been varied, analysed and studied.

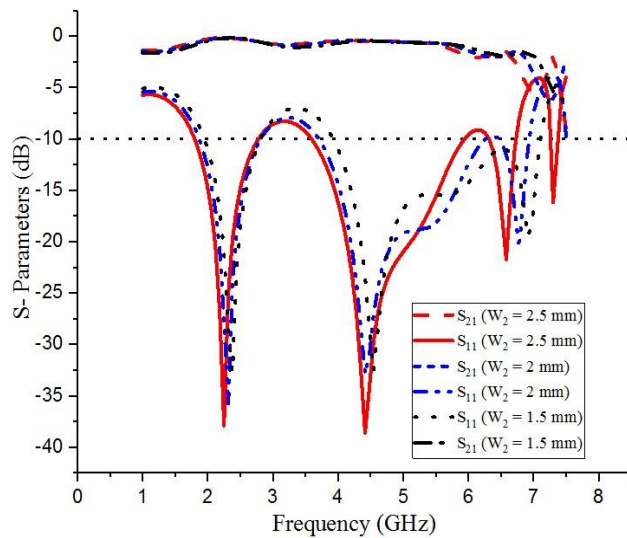


Fig.3 (a). Parametric analysis of S-parameter variations with respect to different values of width of vertical stubs ( $w_2$ )

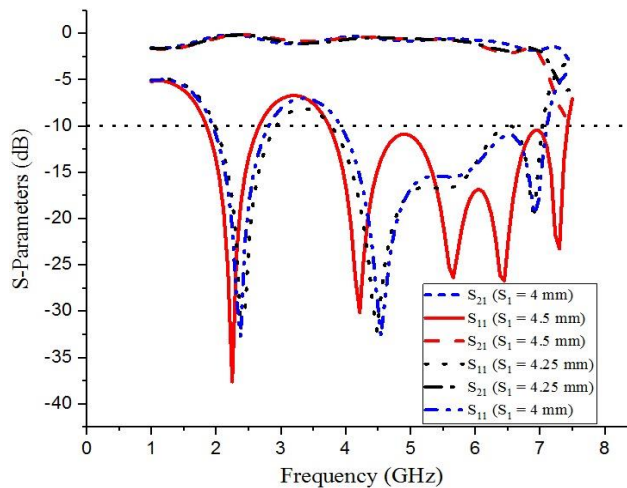


Fig.3 (b). Parametric analysis of S-parameter variations with respect to different values of distance between two vertical stubs ( $S_1$ )

This analysis is carried out to study the effects of – (a) variations in width of horizontal stubs ( $W_2$ ) (b) variation in distance between two vertical stubs ( $S_1$ ) of SIR. This investigation enabled to optimize the design parameters of proposed filter for fabrication purpose. Fig. 3(a) and Fig.3(b) respectively shows the simulated S-parameter variations of the proposed polyester-based wearable bandpass filter. The filter circuit is simulated and results have been verified.

TABLE 1 Parametric analysis of proposed dual band wearable filter

Design parameters (mm)	Resonant frequency (GHz)	FBW (%)	IL (dB)	RL (dB)
$S_1 = 4, W_2 = 1.5$	$f_{r1} = 2.38$	34	0.147	32.6
	$f_{r2} = 4.54$	81	0.469	32.3
$S_1 = 4.25, W_2 = 2$	$f_{r1} = 2.38$	39	0.15	31.1
	$f_{r2} = 4.54$	59	0.462	31.48

The parametric analysis is carried out to study the effect of variations in vertical stub width  $W_2$ . This width  $W_2$  is varied to different values as; 2.5 mm, 2 mm and 1.5 mm respectively. Good impedance matching and effective bandwidth is observed at width  $W_2 = 1.5$  mm as shown in Fig.3 (a). Further, the distance between two vertical stubs ' $S_1$ ' is optimized by varying the values of successive distance between two vertical stubs is  $S_1 = 4$  mm, 4.25 mm, and 4.5 mm respectively. Good impedance matching and bandwidth is observed at distance value  $S_1 = 4$  mm as shown in Fig. 3(b). Table 1 depicts the parametric analysis of proposed wearable bandpass filter. After studying the results, for fabrication the design parameters of SIR are selected as  $W_2 = 1.5$  mm and  $S_1 = 4$  mm respectively.

#### IV. EQUIVALENT CIRCUIT ANALYSIS

The L-C equivalent circuit of proposed filter is prepared and implemented using transmission line theory (TLT). It is prepared by series inductors for high-impedance lines and the low-impedance lines are shunt capacitors. Short length high impedance lines (horizontal stubs) and long length lines (vertical stubs) are grounded. Fig. 4 demonstrates the prepared equivalent circuit schematic of proposed polyester based wearable bandpass filter. TLT is used to prepare equivalent circuit model for the proposed filter and to compute the values of microstrip components such as; inductance and capacitance respectively from their physical dimensions

The SIR has vertical stubs that offer low-impedance line that is capacitances  $C_1, C_3, C_5, C_7, C_9, C_{11}$ , and  $C_{13}$  respectively and high-impedance horizontal stubs provide inductances  $L_2, L_4, L_6, L_8, L_{10}$ , and  $L_{12}$  respectively as shown in Fig.4.

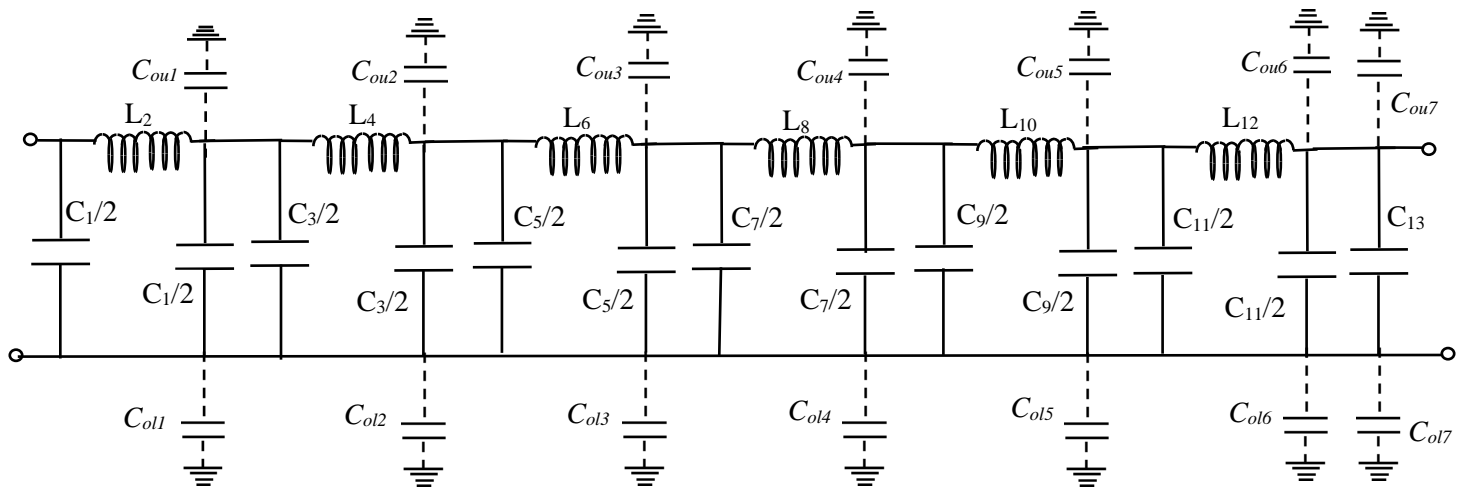


Fig. 4. Equivalent circuit schematic of dual-band polyester-based wearable SIR bandpass filter

These inductances and capacitances of SIR are respectively represented by  $L_2-C_1$ ,  $L_4-C_3$ ,  $L_6-C_5$ ,  $L_8-C_7$ ,  $L_{10}-C_9$ ,  $L_{12}-C_{11}$  and  $C_{13}$ . Further, their values are calculated to 3.45 nH and 1.52 pF using Equations (3) and (4) respectively [7-10].

$$L_s = \left(\frac{Z_0}{g_0}\right) \left(\frac{\Omega_c}{2\pi f_c}\right) g_1 \quad (3)$$

$$C_s = \left(\frac{Z_0}{g_0}\right) \left(\frac{\Omega_c}{2\pi f_c}\right) g_2 \quad (4)$$

where;  $Z_0 = 50 \Omega$ ,  $g_0 = 1$ ,  $g_1 = 1.0316$ ,  $g_2 = 1.1474$ ,  $Z_0 = 50\Omega$ , and  $\Omega_c = 1$ .

In low-impedance line,  $C_{ou1}$ ,  $C_{ou2}$ ,  $C_{ou3}$ ,  $C_{ou4}$ ,  $C_{ou5}$ ,  $C_{ou6}$  and  $C_{ou7}$  as well as  $C_{ol1}$ ,  $C_{ol2}$ ,  $C_{ol3}$ ,  $C_{ol4}$ ,  $C_{ol5}$ ,  $C_{ol6}$  and  $C_{ol7}$  respectively represents the capacitance per unit length between the upper-end and lower-end edges of vertical metal stubs with respect to parallel ground plane. These capacitances per unit length  $C_0$  are calculated using Equation (5) [9].

$$C_0 = \left(\frac{84.73\sqrt{\epsilon_r}}{Z_{01}}\right) pF/inch \quad (5)$$

where;  $Z_{01}$  is total effective electrical length of vertical stub as the measured length plus  $\Delta l$  which is the added length at each end of vertical stub. Hence,  $\Delta l$  and  $C_f$  are calculated using Equation (6) and (7) respectively [9].

$$\Delta l = \frac{0.450W_2 \epsilon_r (C_f')}{C_{01}} \left(\frac{C_f'}{\epsilon}\right) inches \quad (6)$$

where;  $W_2$  is the width of the vertical stub in inches,  $C_f'$  is the effect of fringing capacitance at the edges of both ends of vertical stub with ground. This capacitance is computed by Equation (7) [9].

$$C_f' = \frac{\epsilon}{\pi} \left\{ \frac{2}{1-\frac{t}{W_2}} \cdot \ln \left( \frac{1}{1-\frac{t}{W_2}} + 1 \right) - \left( \frac{1}{1-\frac{t}{W_2}} - 1 \right) \cdot \ln \left[ \left( \frac{1}{(1-\frac{t}{h})^2} - 1 \right) \right] \right\} pF \quad (7)$$

where;  $t$  - is thickness of copper tape,  $\epsilon = 0.225 \cdot \epsilon_r$ , pF per inch. The accounted value of fringing capacitance at the edges of vertical stubs is 0.170 pF/inch. Thus, according to Equation (5), the calculated values of capacitances per unit length at upper-end and lower-end edges of vertical metal stubs with respect to parallel ground plane is 1693.13 pF per inch.

In this filter, due to internal coupling of SIR, additional capacitance is introduced and large capacitive coupling is obtained at the resonator to achieve dual frequency band response with wider bandwidth. The obtained LC equivalent circuit and the calculated component values of proposed filter as shown in Fig.4 has been simulated using an Advanced Design System (ADS) simulator.

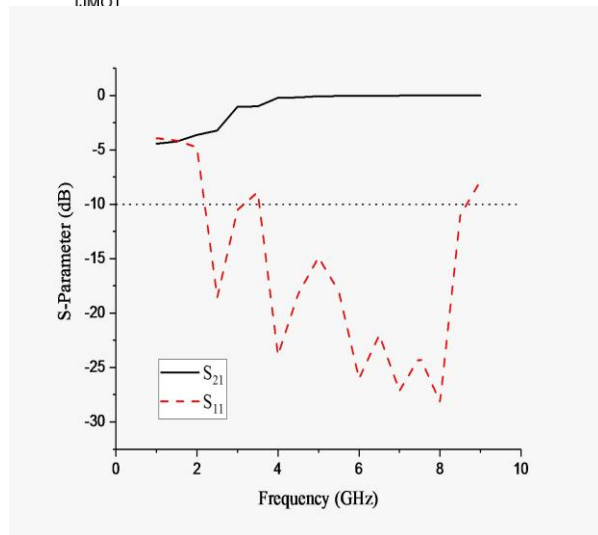


Fig. 5. Frequency response of the proposed wearable SIR filter using ADS simulator

Fig.5 shows the frequency response of proposed wearable SIR filter obtained using an ADS simulator. The resonant frequencies of the proposed SIR filter obtained by equivalent circuit method and obtained by ADS simulator are in good agreement within the frequency ranges of 1.85 GHz to 2.66 GHz band and 3.74 GHz to 7.42 GHz band respectively.

## V. SPECIFIC ABSORPTION RATE (SAR) ANALYSIS

When the wearable filter is put on human body the electromagnetic signals get penetrated and absorbed in the biological tissues of human body.

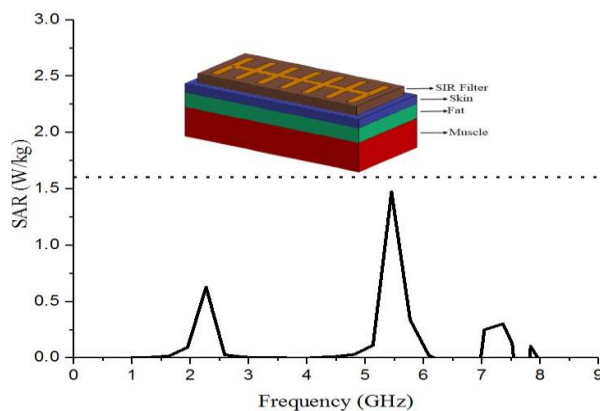


Fig. 6. SAR response of dual-band polyester-based wearable bandpass filter.

The specific absorption rate (SAR) analysis is used to examine the absorption of electromagnetic signals in the tissues and muscles of human body [7], [19]. Hence, the effect of proposed wearable SIR filter on human body is investigated by performing SAR calculations using CAD Feko simulator at resonant frequencies 2.38 GHz and 4.54 GHz respectively. The Federal communications commission (FCC) and ICNIRP International Electrotechnical Commission (IEC) recommended limiting SAR values to 1.6 or 2 W/kg. Fig.6 shows the SAR response of proposed SIR wearable filter that is determined by the CAD Feko simulator.

In this study, SAR value of the SIR filter at the skin, fat, and muscle of the human body was found to be 0.6 W/kg at 2.38 GHz and 0.24 W/kg at 4.54 GHz respectively which is in good agreement. Therefore, the proposed polyester based SIR filter is appropriate for wearable applications and can be installed on the human body.

## VI. MEASURED RESULTS

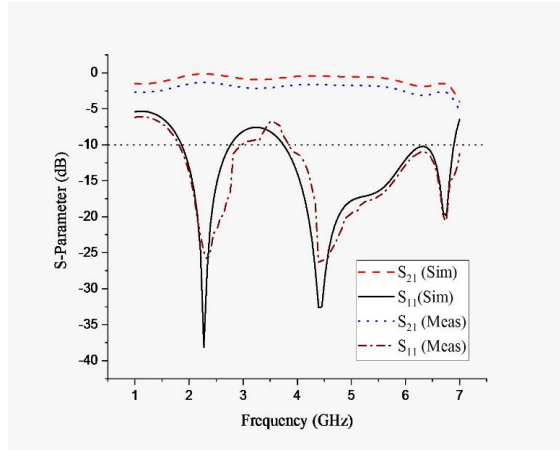
The fabricated SIR filter is tested using Agilent Technologies Keysight RF Vector network analyzer N9923A 6GHz, in accordance with the optimised design parameters indicated in the parametric analysis. Fig. 7 (a) depicts the simulated and measured insertion loss ( $S_{21}$ ) and return loss ( $S_{11}$ ) results of the fabricated dual-band polyester-based wearable SIR filter circuit.

Fig.7 (b) depicts the measurement set-up photograph. The results shows pass bands at 2.38 GHz and 4.54 GHz respectively. The measured return loss ( $S_{11}$ ) is 36.6 dB and insertion loss is 0.095 dB at resonant frequency 2.38 GHz. Similarly, at 4.54 GHz the measured return loss ( $S_{11}$ ) is 44.3 dB and insertion loss is 0.36 dB. The frequency transformation is  $\Omega = 0.417$  at 2.38 GHz and  $\Omega = 0.213$  at 4.54 GHz respectively.

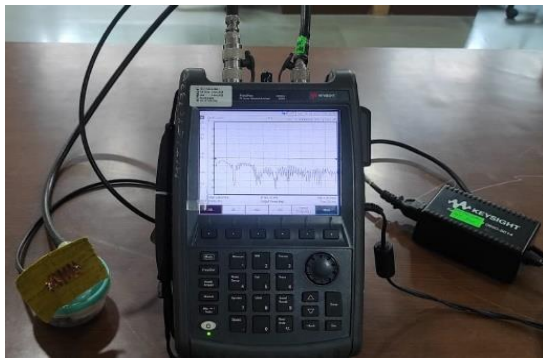
The simulated and measurements results of proposed SIR filter at both resonant frequencies are in well agreement. This is a wearable planar circuit useful for ISM and Wi-Fi, WLAN and Wi-Max frequency band applications.



The proposed filter is entirely handmade therefore some variations in the measured results may be observed. If the copper tape will be cut using CNC machine, then variations in results will be eliminated. Numerous rigid and wearable filters are designed, fabricated and published in the literature. Therefore, the results of proposed filter are compared with the results of published filters to validate the findings.



(a)



(b)

Fig. 7 (a). Simulated and measured S-parameter results of the fabricated dual-band polyester-based wearable bandpass filter. (b) Photograph of measurement set-up

Table 2 illustrates the performance comparison between published rigid and wearable bandpass filters and wearable bandpass filter. In Table 2, IL is insertion loss, RL is return loss and FBW is fractional bandwidth at corresponding centre frequencies of pass-band. In References [5] and [7], single-band wearable filter using wearable LCP and polyetser substrates is reported whereas, in References [16-17] the results of rigid filter are presented. Further, the results of dual-band

wearable SIR filter using polyetser substrate are presented and compared which are in good agreement. The VSWR of referred filter circuits are compared and presented in the Table 2. In the proposed filter circuit the VSWR is approximately 1 at both frequency bands. As compared to other filters the FBW at both the resonant bands is large due to capacitive coupling as shown in the equivalent circuit.

The pivotal parameters affecting the performance parameters of SIR filter are dimensions of vertical stubs because of its fringing capacitance bandwidth is enhanced. The fringing capacitance increases the electrical length of the SIR. The resonant frequencies are decided by inductance and capacitance offered by horizontal stubs. The comparative parameters of Table 2 IL, RL, VSWR, sharpness of the simulated and measured bands, size of the filter shows utility of the filter for various wireless communication systems.

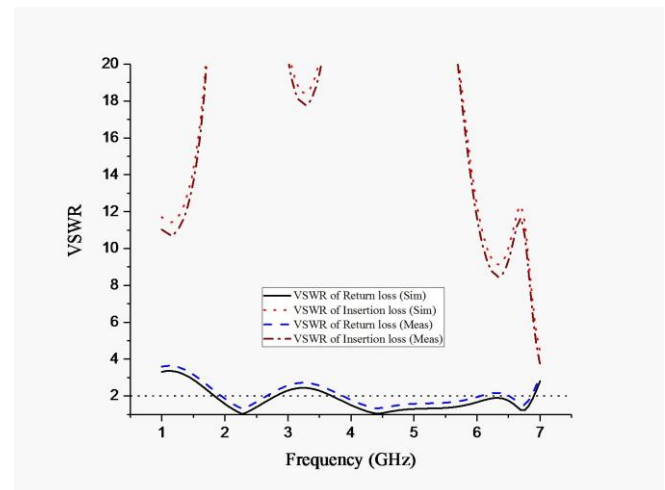


Fig. 8. Comparison of Simulated and measured VSWR at return loss and insertion loss of fabricated dual-band polyester-based wearable bandpass filter using SIR.

Fig. 8 shows the comparison of simulated and measured VSWR at return loss ( $S_{11}$ ) and insertion loss ( $S_{21}$ ) of the fabricated wearable SIR filter. The VSWR values are good in agreement and also indicated in Table 2. As compared to published results the proposed filter has- (a) better impedance matching is also obtained (b) FBWs of fabricated filter are wide and in good agreement with simulated results.



TABLE 2: Comparison between published filters and proposed wearable filter

Ref.	$f_0$ (GHz)	IL (dB)	RL (dB)			FBW (%)	Substrate used	Size
			$S_{11}$	VSWR (Sim)	VSWR (Mea)			
[16] Single-band filter	1.415	1.42	20	1.22	--	9.3	Taconic-RF35 (Rigid)	$0.162 \lambda_g \times 0.21 \lambda_g$
[17] Dual-band bandpass filter	2.4	0.22	15	1.43	--	8.3	RT/Duroid 5880 (Rigid)	$0.162 \lambda_g \times 0.075 \lambda_g$
	5.7	0.56	21	1.20	--	3.5		
[18] Dual-band bandpass filter	2.4	0.64	22	1.17	--	2.92	RT/Duroid 5880 (Rigid)	$0.126 \lambda_g \times 0.132 \lambda_g$
	5.7	0.76	21.3	1.18	--	1.67		
[5] Single-band filter	5.61	1.9	6.5	1.35	--	12.9	Liquid crystal polymer (LCP) (Wearable)	$0.122 \lambda \times 0.183 \lambda$
[7] Single-bandpass wearable filter	4.48	0.87	35.9	1.03	--	5.58	Polyester (Wearable)	$0.427 \lambda \times 0.195 \lambda$
Proposed work (Dual-Bandpass Wearable Filter)	2.38	0.147	32.6	1.05	1.02	34	Polyester (Wearable)	$0.46 \lambda \times 0.261 \lambda$
	4.54	0.469	32.3	1.05	1.02	81		

Thus, the proposed wearable filter is a good candidate for wearable RF and wireless communication applications. This filter can be connected with polyetser based wearable microstrip patch antenna that is wearable filtenna applicable for wearable ISM, WLAN, and Wi-Max systems. This filter is useful to remove the noise interference in application frequency band and to achieve better frequency selectivity. Advantages of proposed wearable filter are; application specific dual-band performance, low cost, design flexibility, compact design, excellent performace capabilities and hence furthest suitable for wearable RF communication devices, wearable electronic devices and systems. Greater accuracy is required to maintain the uniform thickness of substrate during manufacturing process.

## VII. CONCLUSION

This research paper presents a compact wearable dual-band SIR filter based on polyetser cloth for ISM, WLAN, and Wi-Max frequency bands. LC equivalent circuit of proposed filter is prepared and analyzed. Good agreement is obtained between simulated and measured insertion and return loss results at 2.38 GHz and 4.54 GHz respectively. The SAR values of proposed filter at resonant frequencies are found in good agreement. Comparison with other rigid and flexible filter shows that the proposed filter is able to meet requirements of dual-band wearable filter applications. Limitations of rigid microstrip filters for wearable applications may be eliminated using this type of filters.

## REFERENCES

- [1] J.G. Joshi, S.S. Pattnaik, and S. Devi, "Metamaterial embedded wearable rectangular microstrip patch antenna," *International Journal of Antennas and Propagation*. July 2012; 2012:1-9 (Special issue on Wearable Antennas and Systems, Hindawi Publication Corporation ID. 974315) doi: 10.1155/2012/974315.
- [2] J.G. Joshi, S.S. Pattnaik, and S. Devi, "Geo-textile based metamaterial loaded wearable microstrip patch antenna," *International Journal of Microwave and Optical Technology*, Vol. 8, No.1, pp.25-33, January 2013.
- [3] J.G. Joshi, and S.S. Pattnaik, "Metamaterial based wearable microstrip patch antennas," *Handbook of Research on Wireless Communications and Networking-Theory and Practice*, Chapter 20, Information Science Reference IGI Global, USA, February 2014, 518-556, DOI: 10.4018/978-1-4666-5170-8, ISBN 13:9781466651708.
- [4] J. G. Joshi, M. P. Joshi, and S.S. Pattnaik, "Embroidered dual band wearable microstrip patch antenna," *Transactions on Electromagnetic Spectrum*, Vol.3, No.1, pp. 51–58, October 2023. <https://doi.org/10.5281/zenodo.10020917>.
- [5] Zhao Mengjuan and Zhang Yong, "A compact wearable 5-GHz flexible filter," *IET Electronics Letters*, Vol. 53, No. 10, pp. 661-663, May 2017. <https://doi.org/10.1049/el.2017.0625>.
- [6] Bahareh Moradi, Raul Fernández-García, and Ignacio Gil Gali, "E-textile metamaterials: stop band pass filter," *MDPI Applied Sciences*, 11, 10930, pp.1-5, November 2021;. <https://doi.org/10.3390/app112210930>.
- [7] J.G. Joshi, S. Raghavan, and S.S. Pattnaik, "Polyester-based wearable bandpass microstrip filter," *Microwave Optical Technology Letters*, Vo.6, No.12, pp.3069-3075, December 2023. doi:10.1002/mop.33827.
- [8] Seymour B. Cohn, "Analysis of a wide-band waveguide filter," *Proceedings of The I.R.E.* Vol. 37, No. 6, pp. 651-656, June 1949.
- [9] George L. Matthaei, Leo Young, E. M. T. Jones, "*Microwave filters, impedance-matching networks, and coupling structures*," Artech House Inc; Norwood, November 1985.
- [10] J-S Hong, "Microstrip Filters for RF/Microwave Applications," 2nd ed. New Wiley A John Wiley & Sons Inc. Publications; 2011.



- [11] Jen-Tsai Kuo, and Eric Shih, "Microstrip stepped impedance resonator bandpass filter with an extended optimal rejection bandwidth," *IEEE Transactions on Microwave Theory and Techniques*, Vol.51, No.5, pp. 1554-1559, May 2003.
- [12] Zhou W, Liu C, Huang G-L, Wei Xia, Jingwei Z., Daping He, Zhi Wu, "Design and manufacture of lowpass microstrip filter with high conductivity graphene film," *Microwave Optical Technology Letters*, Vol.61, No. 4, pp.972-978, April 2019. DOI: 10.1002/mop.31693.
- [13] J. Naqui M. Duran-Sindreu J. Bonache F. Martin, "Implementation of shunt-connected series resonators through stepped-impedance shunt stubs: analysis and limitations," *IET Microwave Antennas Propagation*, Vol.5, No.11, pp.1336-1342, August 2011. doi: 10.1049/iet.map.2010.0612.
- [14] Mitsuo Makimoto and Sadahiko Yamashita, "Bandpass filters using parallel coupled stripline stepped impedance resonators," *IEEE Transactions on Microwave Theory and Techniques*, Vol. MTT-28 No.12, pp. 1413-1417, December 1980.
- [15] PK Singh, S.Basu, YH.Wang, "Planar ultra-wideband bandpass filter using edge coupled microstrip lines and stepped impedance open stub," *IEEE Microwave and Wireless Components Letters*, Vol.17, No.9, pp. 649-665, September 2007.
- [16] D. Li, Ju-An Wang, Z. Chen, Y. Zhang, M-C. Tang, L.Yang, "Compact microstrip bandpass filter with sharp roll-off broad stopband using modified 0° feed structure," *Elsevier International Journal of Electronics and Communications (AEU)*, Vol.109, pp.17-22, July 2019.
- [17] S. Khani, SMH Mousavi, M Danaie, P. Rezaei, "Tunable compact microstrip dual-band bandpass filter with tapered resonators," *Microwave and Optical Technology Letters*, Vol. 60, No.5, pp.1256-1261, May 2018.
- [18] S. Khani, SMH Mousavi, M Danaie, P. Rezaei, "Adjustable compact dual-band microstrip bandpass filter using T-shaped resonators," *Microwave and Optical Technology Letters*, Vol. 59, No.12, pp.2970-2975, December 2017.
- [19] K Guido, and A. Kiourti, "Wireless wearables and implants: A dosimetry review," *Bioelectromagnetics Wiley Periodicals, Inc.* Vol. 41, No.1, pp.3-20, January 2020.